Behavioural Brain Research 304 (2016) 111–119

Contents lists available at ScienceDirect

Behavioural Brain Research

journal homepage: www.elsevier.com/locate/bbr

Research report

Abnormal visual experience during development alters the early stages of visual-tactile integration

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HIGHLIGHTS

- Abnormal visual experience during development alters crossmodal interactions in adults.
- The ability to use vision selectively to modulate the processing of task-relevant tactile input is reduced.
- Processing of tactile input is enhanced in people with abnormal binocular vision.
- Tactile input may facilitate visual processing.

ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form 10 February 2016
Accepted 13 February 2016
Available online 16 February 2016

Keywords:
Event-related potentials
Somatosensory cortex
Multisensory integration
Binocular vision
Attention

ABSTRACT

Visual experience during the critical periods in early postnatal life is necessary for the normal development of the visual system. Disruption of visual input during this period results in amblyopia, which is associated with reduced activation of the striate and extrastriate cortices. It is well known that visual input converges with other sensory signals and exerts a significant influence on cortical processing in multiple association areas. Recent work in healthy adults has also shown that task-relevant visual input can modulate neural excitability at very early stages of information processing in the primary somatosensory cortex. Here we used electroencephalography to investigate visual-tactile interactions in adults with abnormal binocular vision due to amblyopia and strabismus. Results showed three main findings. First, in comparison to a visually normal control group, participants with abnormal vision had a significantly lower amplitude of the P50 somatosensory event related potential (ERP) when visual and tactile stimuli were presented concurrently. Second, the amplitude of the P100 somatosensory ERP was significantly greater in participants with abnormal vision. These results indicate that task relevant visual input does not significantly influence the excitability of the primary somatosensory cortex, instead, the excitability of the secondary somatosensory cortex is increased. Third, participants with abnormal vision had a higher amplitude of the P1 visual ERP when a tactile stimulus was presented concurrently. Importantly, these results were not modulated by viewing condition, which indicates that the impact of amblyopia on crossmodal interactions is not simply related to the reduced visual acuity as it was evident when viewing with the unaffected eye and binocularly. These results indicate that the consequences of abnormal visual experience on neurophysiological processing extend beyond the primary and secondary visual areas to other modality-specific areas.

1. Introduction

Imaging and electrophysiological studies have shown that multisensory integration is a fundamental aspect of human information processing [1,2]. Psychophysical evidence supports that the ability to process and integrate inputs from multiple modalities offers many behavioural benefits, including improved precision of feature discrimination [3], faster reaction time [4], and more precise target localization [5]. The traditional view of multisensory integration has been that sensory inputs from different modalities converge onto neurons in the higher order cortical association areas, such as the parietal, temporal, and frontal cortices. More recent studies have shown that the neural excitability of primary sensory cortices can be modulated by the presence of a stimulus from another modality, when the stimulus is behaviourally relevant [6], and even

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http://dx.doi.org/10.1016/j.bbr.2016.02.018
0166-4328/

when the stimulus is not relevant to the current task performance [7]. This indicates that crossmodal interactions are present at the early stages of modality-specific processing in adults with normal sensory function. Multiple imaging studies have shown that abnormal visual experience during development affects the anatomical organization and neural responses in the striate and extrastriate cortices; however, it is currently unknown whether the disruption of visual input during development affects crossmodal interactions. Here we used electroencephalography (EEG) to investigate the effects of abnormal visual experience during childhood due to amblyopia and strabismus on the early stages of visual-tactile interactions.

Studies have shown that cross modal interactions in visually normal people can be affected by bottom-up sensory input and top-down modulation [8]. The bottom up factors that can influence crossmodal interactions include stimulus properties (i.e. salience) and characteristics of the sensory modality (i.e., spatial and temporal response properties of the receptors, which poses structural limits on the precision and accuracy of the sensory input). The top down factors include experimental instructions, prior experience and assumptions about the stimulus. Both bottom up and top down factors interact and affect the deployment of attention and behavioural responses. In particular, observers are more likely to allocate more attention to the modality that has provided more reliable information in the past. However, situational factors, such as salience, instructions and task demands have also been shown to change the allocation of attention.

The temporal aspects of crossmodal interactions can be studied using EEG, which is notable for its temporal resolution. Research has shown that significant crossmodal interactions occur during early sensory processing stages. For example, studies with visually normal adults have shown that a task-relevant visual stimulus modulates the neural excitability of the primary (S1) and secondary (S2) somatosensory cortices [9]. Specifically, the amplitude of the P50 event related potential (ERP), which is commonly observed between 40 ms–60 ms following stimulus onset [10] and is thought to reflect S1 excitability [11], was enhanced when both sensory stimuli were behaviourally relevant. In contrast, the amplitude of the P100 ERP component, generated in S2, was enhanced during tactile-visual stimulation, but it was not modulated by task relevancy. Specifically, the somatosensory P100 amplitude was comparable in the crossmodal conditions whether or not the tactile stimulus was task relevant and required a motor response. In a follow-up study, Popovich and Staines [12] examined the effects of visual priming (bottom-up salient sensory input) and task-relevance (top-down attention) on S1 activation. Top-down modulation was assessed by instructing subjects to attend to crossmodal (visual/tactile) stimuli, which required a motor response, and to ignore the unimodal (tactile/tactile or visual/visual) condition, which did not require a motor response. To assess the role of visual priming on S1 excitability, the visual stimulus was presented 100 ms prior to the tactile stimulus, simultaneously, or 100 ms after the tactile stimulus. This manipulation allowed to tease out the contribution of visual priming on S1 excitability. If vision exerts influence via a bottom up mechanism, the greatest modulation was expected in a condition when visual input was presented 100 ms prior to the tactile stimulus. In contrast, no effect of vision was expected in a condition when the visual input was presented after the tactile stimulus. Results showed the greatest enhancement of the P50 ERP amplitude occurred in a condition when subjects were instructed to attend to the visual stimulus, and the visual stimulus preceded the tactile stimulus. These findings indicate that vision plays an important role in modulating the early stages of somatosensory processing, and that these crossmodal effects are mediated by both bottom-up sensory interactions and top-down behavioural relevance.

Spatially and temporally congruent visual input to both eyes during the critical periods in early postnatal life is necessary for the normal development of the visual system [13]. Disruption of the visual input due to eye misalignment (strabismus), unequal refractive error (anisometropia), or form deprivation during this period results in amblyopia (lazy eye). Amblyopia has been used extensively to study the development of the visual system and the critical periods of plasticity [14–18]. Human neuroimaging studies in amblyopia have shown reduced activation in the striate and extrastriate areas (for recent reviews see [19–21]). Studies that examined the effects of amblyopia on higher perceptual processes, such as visual decision-making and attentional processes, provided mixed results. For example, recent studies with humans and amblyopic monkeys that examined endogenous and exogenous attention shifts using a Posner type paradigm reported that amblyopic individuals perform with a comparable level of accuracy and speed of responding when compared to a visually-normal control group [22–24]. These authors concluded that the underlying mechanism used to shift attention based on a visual cue remains intact. In contrast, other studies that examined visual processing during the performance of more complex tasks, including multiple object tracking [25], discrimination of a target among incongruent distracters [26], visual search for conjunctions [27], attentional blink [28], or object enumeration [29], found significantly lower performance in people with amblyopia. Moreover, deficits on some of these tasks were evident across all viewing conditions.

There is limited knowledge about the effects of abnormal visual experience on crossmodal interactions in people with amblyopia. A recent neuroimaging study has shown enhanced responses in the occipital areas during auditory stimulation in people with amblyopia who experienced a relatively brief visual deprivation due to congenital dense cataracts [30]. Other studies have examined audiovisual integration in adults and children with amblyopia using the McGurk effect, which is an audiovisual illusion resulting from fusing incongruent auditory and visual syllables presented concurrently [31–33]. Results showed that people with amblyopia had a reduced McGurk effect and increased variability in reporting the illusion, which indicates weaker audiovisual integration. These studies offered initial evidence that the development and cortical function in regions involved in audiovisual integration, such as the superior temporal sulcus [34], may be affected by abnormal binocular visual experience during childhood. However, the effects of amblyopia on other aspects of crossmodal interactions at the behavioural or neurophysiological level are currently unknown.

The aim of the current study was to investigate the effects of disrupted visual processing due to amblyopia and strabismus on the early stages of crossmodal interactions using EEG. Since the visual modality provides less reliable sensory information in people who experienced abnormal vision during childhood, it was expected that both, the bottom up and top down mechanism involving crossmodal interactions will be affected. Specifically, we used a paradigm developed by Staines and colleagues [9,12] to investigate the effect of visual priming (bottom up sensory input) and instructions (top down modulation) on the early somatosensory ERP components, P50 and P100. We hypothesized that task relevant visual input will have a reduced effect on the excitability of the somatosensory P50 ERP component in people who experienced abnormal visual development when compared to visually normal participants. Because somatosensory processing is likely to be intact and provide more reliable sensory input compared to vision, we also expected that the amplitude of the P100 will be greater in the experimental group. Finally, our paradigm allowed us to investigate the effect of vibrotactile stimulation on the neural excitability of the visual cortex by examining an early positive visual ERP, P1. Previous studies have shown that the amplitude of the P1 ERP, elicited between 90 and 150 ms, is modulated by cross-